Temporal Stability of Spatially Measured Soil Matric Potential Probability Density Function

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ABSTRACT

Estimation of mean water status in a field is crucial to effective irrigation water management. Problems encountered with the estimation of mean field soil water status may be attributed to spatial variability of soil physical properties. Several investigators have shown temporal stability of spatial patterns of field measured soil water content, but temporal stability of field measured soil matric potential (ψ_m), a measure of soil water status more appropriate for irrigation scheduling, has not previously been reported to last for more than a few days within one irrigation cycle. This study investigated the temporal stability of spatial patterns of ψ_m both within and between sequential irrigation cycles. Sixty locations in a 1-ha field were outfitted with a 1-m neutron probe access tube and three tensiometers placed at 0.15-, 0.3-, and 0.5-m depths. The observations obtained from 14 d of soil water content measurements and 46 d of ψ_m measurements within eight irrigation cycles were analyzed with Spearman's rank correlation coefficients and a relative differencing technique. The results showed temporally stable soil water content spatial patterns and also indicated temporally stable ψ_m spatial patterns if assumptions of full soil wetting at the beginning of the cycle and uniform evapotranspiration among locations were satisfied. Several locations in the field estimated the field mean ψ_m to within 10% within a given range of potentials, and a few estimated the field mean to within 20% across the entire range of potentials tested. Other locations estimated the lower and higher percentiles of ψ_m with similar accuracy.

In most areas of the western USA and several areas of the world, irrigated agriculture is the predominant user of water. Irrigation water is applied to crops in a variety of ways, including surface, sprinkler, and drip irrigation systems, with application efficiencies ranging from 40 to 95%. Improvements in irrigation efficiency are often possible through better irrigation system design and knowledge of the soil water properties of the irrigated fields. Unfortunately, determination of the soil water properties in a given field is often complicated by the large spatial variability of these properties.

Soil spatial variability has been the focus of considerable research during the last three decades. In addition to field studies (Nielsen et al., 1973; Greminger et al., 1985; Kachanoski et al., 1985; Saddiq et al., 1985; Bresler, 1989; Goovaerts and Chiang, 1993), the application of geostatistics, particularly kriging and cokriging (Vauclin et al., 1983), and scaling theory (Simmons et al., 1979; Russo and Bresler, 1980; Western and Bloschl, 1999) have been steps toward the characterization of fields on the basis of the variability of observations from those fields. Both of these techniques, however, require more observations than are practical for most field managers. Efforts have been made to characterize fields from fewer observations. The application of bootstrapping techniques (Dane et al., 1986) has been used to estimate the minimum number of observations necessary for the reliable estimation of soil parameters in a variable field.

A number of studies (Ottoni, 1984; Vachaud et al., 1985; Kachanoski and de Jong, 1988; van Wesenbeeck and Kachanoski, 1988; Jaynes and Hunsaker, 1989; Goovaerts and Chiang, 1993; Chen et al., 1995) have shown that, although soil water content varies with time and with location in the field, the pattern of spatial variability does not change with time when the observations are ranked according to the magnitude of soil water content or scaled against the field mean soil water content. This phenomenon has been termed *temporal stability*. The covariants of significance in these cases were determined to be primarily soil texture and topography. The dependence of water content upon soil texture has also been used to locate textural boundaries in a field from measurements of soil water content along a transect in an irrigated field soil (Hendrickx et al., 1986).

Although temporal stability has been demonstrated for soil water contents, it has not been shown for ψ_m. Soil matric potential is assumed to change with changes in soil water content. However, this function is nonlinear and may be expected to have a spatial component of variability as well (Taylor and Ashcroft, 1972; Shouse et al., 1995). Problems encountered with the measurement of ψ_m using tensiometers have included the variability of measurements at a single location by hysteresis, by mechanical influences of shrinking and swelling soils, and by the effects of diurnal temperature fluctuations (Taylor and Ashcroft, 1972; Jackson, 1973; Warrick et al., 1998). In spite of these measurement problems, ψ_m is regarded as the best measure of soil water availability for crops (Taylor, 1952, 1965; Kramer, 1983).

The literature offers little information directly relevant to temporal stability of ψ_m in field soils. Saddiq et al. (1985) reported that variability and spatial dependence were a function of method of water application, time after water application, and the magnitude of the mean field ψ_m. Hendrickx and Wierenga (1990) noted that temporal stability of ψ_m persisted for only one irrigation interval. They proposed the use of about seven tensiometers in a given field to estimate the mean ψ_m, but also advised using a value of threshold ψ_m less negative than the crop critical threshold for initiation of irrigation. In a subsequent study, Hendrickx et al. (1994) determined that tensiometer cup size greatly influenced measurement variability and noted that large tensiometer cups

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Published in Soil Sci. Soc. Am. J. 65:668–677 (2001).

Abbreviations: ψ_m, soil matric potential.

with 88.3-cm^2 surface area could be used to reduce the number of measurement locations required to estimate mean field ψ_m down to four.

It would seem preferable to find a single location in a given field approximating either the mean or a chosen percentile of ψ_m from which to schedule irrigation. Such a location would allow quick and inexpensive monitoring of crop available soil water and could possibly serve as the sensor location from which automated irrigation systems would be activated. This facility would provide a convenient tool by which irrigation and water use efficiencies could be optimized.

This study was undertaken to develop a procedure to find a location in a field that would provide a ψ_m measurement consistent with the mean or given percentile value for the whole field. In order to accomplish this objective it was deemed necessary to (i) validate, with data collected from a field of Glendale clay loam, previous work regarding the temporal stability of soil water contents; (ii) determine if temporal stability of ψ_m could be established in the same field; and (iii) attempt to elucidate a simple covariant with ψ_m that would allow identification of optimal sampling locations without the use of extensive ψ_m sampling to characterize the field.

MATERIALS AND METHODS

A 1-ha field of Glendale silty clay loam (fine-loamy, mixed, calcareous, thermic Typic Torrifluvent) at the Leyendecker Plant Science Research Center near Las Cruces, NM was the site for the experiment. The surface soil layer is clay loam of varying depths, and soil below this mixed surface layer is highly layered, the textures highly variable, and the textural boundaries abrupt. The field was planted to spring wheat (*Triticum vulgare* L.) in early February 1989 and had been planted to cotton (*Gossypium hirsutum* L.) for the previous two growing seasons.

The field was trickle irrigated using subsurface trickle tape (Chapin Watermatics, Watertown, NY) with emitter spacings of 0.3 m and water control orifice spacings of 1.5 m.[1] The tape was installed in the field on 1-m centers and buried at a depth of 0.25 m. The irrigation system was constructed and the field divided so that water could be applied to as few as six or as many as 120 rows. The field was thus divided into 20 water treatment blocks of six rows each and, for this study, each treatment block received the same amount of water. The use of individually metered treatment blocks provided verification of uniform water application and proper system operation across the entire field. A diagram of the experimental field and irrigation system is presented in Fig. 1.

Within each of the 20 treatment blocks, three sampling locations identified by the numbers in Fig. 1 were established at intervals of 22 m. At each of the sampling locations, three tensiometers were placed 0.15 m north of the trickle tape and at depths of 0.15, 0.3, and 0.5 m below the surface, resulting in a total of 180 individual tensiometers. Neutron probe access tubes were installed 0.15 m south of the trickle tape and opposite the 0.3-m tensiometer at each of the 60 field locations.

The wheat was planted the second week of February 1989 with a grain drill in 0.25-m spaced rows continuously across the field. After an initial irrigation of 0.25 m, irrigation was applied in 0.1-m depths at intervals of ≈10 d beginning on 6 April. The irrigation interval was reduced to ≈8 d in mid May, and the depth was reduced to 0.075 m for the 6 June irrigation. The final irrigation of 0.025 m occurred on 10 June.

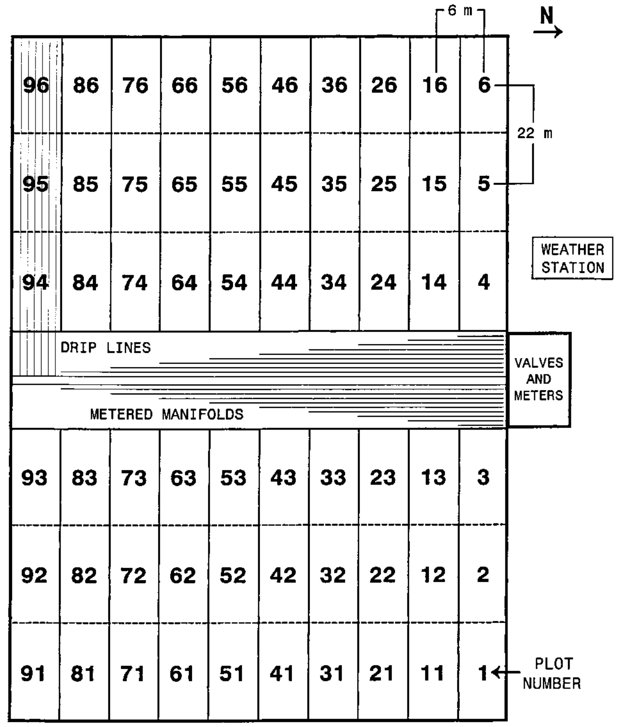

Fig. 1. Diagram of the field used for the study showing location numbers. Instrumentation was placed at the center of each plot. Solid lines in the center of the diagram represent irrigation system manifolds, and the dashed lines through plots 94 through 96 represent subsurface trickle irrigation lines that ran through each plot.

Data collection began on 5 April, the day prior to the first 0.1-m irrigation. Soil water content data were collected for the 0.15-, 0.3-, and 0.5-m depths with a neutron moisture meter (Hydroprobe Model CPN003, Campbell Pacific Nuclear, San Diego, CA) that had been calibrated at 18 locations in the field at the time of access tube installation. Soil water contents at the time of calibration ranged from 0.20 to 0.33, 0.16 to 0.36, and 0.10 to 0.50 for the 0.15-, 0.3-, and 0.5-m depths, respectively. Soil water storage measurements were taken ≈48 h postirrigation and again near the end of the irrigation interval. A total of 14 d of soil water content data were collected between 15 April and 6 June. ψ_m was measured with a Tensicorder, a hand-held pressure transducer with memory (Soil Measurement Systems, Tucson, AZ) according to Marthaler et al. (1983). ψ_m Measurements were taken on the days of soil water content measurement and on an additional 32 d for a total of 46 d between 5 April and 15 June.

Following the period of soil water measurement, the instrumentation was removed and the destructive sampling of the field was initiated. The wheat in a 1-m^2 plot around each sampling location was clipped and oven dried for total aboveground dry matter. A soil core 1 m long and 0.05 m in diameter was extracted from each sampling location 0.15 m west of neutron probe installation. The core was measured for depth to textural boundaries and the upper 0.6 m was divided into three 0.2-m segments, dried, crushed, and analyzed for the percentage of sand (particles >50 μm diam.) using the hydrometer method (Gee and Bauder, 1986). Soil bulk density measurements were taken for the 0.15-, 0.3-, and 0.5-m depths

[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

of measurement at four locations in the field using a removable ring soil coring device (Blake and Hartge, 1986).

Soil water contents were calculated from the neutron meter counts, multiplied by 0.2 m (the incremental soil depth that the measurement represented) to yield soil water storage depth, and summed by location across the three depths of measurement. Field mean water storage and associated variances were calculated for each day of measurement. Intertemporal means and variances were calculated for mean water storage depth both for 48 h postirrigation and change in water content between measurement dates by location.

Tensicorder readings were corrected for depth of measurement to give ψ_m measurements. In order to be retained for analysis, ψ_m had to be less than zero and the locations were deleted from a given cycle if the first postirrigation measurement was less than −20 kPa, indicating insufficient wetting of the area around the tensiometer cups resulting from plugged emitters or insufficient lateral movement from the emitter. The remaining depth-corrected data for each location were averaged across the three measurement depths to yield mean ψ_m for each location and day of measurement. These mean depth-corrected ψ_m by location formed one dataset for analysis, and the depth-corrected readings from the 0.3-m measurement depth formed the other dataset. These two datasets were analyzed separately and compared to test the efficacy of using one measurement depth to estimate the mean ψ_m in the rootzone of the soil profile.

Field mean ψ_m was calculated for each measurement day, and locations were ranked from lowest to highest ψ_m for each day. The data and ranks from each day of measurement were placed into one of twelve categories based on field mean ψ_m. The following limits were used to define the categories.

1. $-10 \text{ kPa} < \psi_m \leq -5 \text{ kPa}$
2. $-15 \text{ kPa} < \psi_m \leq -10 \text{ kPa}$
3. $-20 \text{ kPa} < \psi_m \leq -15 \text{ kPa}$
4. $-25 \text{ kPa} < \psi_m \leq -20 \text{ kPa}$
5. $-30 \text{ kPa} < \psi_m \leq -25 \text{ kPa}$
6. $-35 \text{ kPa} < \psi_m \leq -30 \text{ kPa}$
7. $-40 \text{ kPa} < \psi_m \leq -35 \text{ kPa}$
8. $-45 \text{ kPa} < \psi_m \leq -40 \text{ kPa}$
9. $-50 \text{ kPa} < \psi_m \leq -45 \text{ kPa}$
10. $-55 \text{ kPa} < \psi_m \leq -50 \text{ kPa}$
11. $-60 \text{ kPa} < \psi_m \leq -55 \text{ kPa}$
12. $\psi_m < -60 \text{ kPa}$

This grouping of data provided a way of testing for temporal stability of ψ_m measurements at discrete levels that might correspond with critical thresholds used for irrigation scheduling. The grouping also allowed for inspection of the intertemporal mean rank stability at each location as the field mean ψ_m changed. For many of the analyses, Categories 1 and 2 were combined, as were Categories 3 and 4. These ranges were combined to simplify presentation of the results. With the first four categories combined into two and no observations in Category 12, nine categories were used to test for temporal stability in most of the analyses.

Hendrickx and Wierenga (1990) reported ψ_m measurements were not always distributed normally. They also noted that the variance increased with the magnitude of the means. By ranking the data, the locations were placed on an ordinal scale and individual days of measurement could be compared. The nonparametric method of Spearman's rank correlation coefficients (Snedecor and Cochran, 1967) was employed to test for temporal stability of soil water content and ψ_m among the locations. Spearman's rank correlation coefficient r_s is calculated by

$$r_s = 1 - \frac{6\sum_{i=1}^{n}(R_{ij} - R_{ij}')^2}{n(n^2 - 1)} \quad [1]$$

where n is the number of observations (locations) compared, R_{ij} is the rank of soil water measurement (storage or ψ_m) at location i (i = 1–57) on day j (j = 1–14 for storage and j = 1–46 for ψ_m), and R_{ij}' is the rank of soil water measurement at the same location on another day j'.

A parametric test of relative differencing, as used by Vachaud et al. (1985) was employed to graphically present the data in a manner that would reveal differences in the constancy of temporal stability among locations. The relative differencing technique scales the measurements from each location against the associated field mean, thus stabilizing the variance due to the changing value of the daily field means. The relative difference δ_{ij} is calculated by

$$\delta_{ij} = \frac{\Delta_{ij}}{\bar{S}_j} \quad [2]$$

where Δ_{ij} is calculated by subtracting the field mean measurement for day j, $\bar{S}_j$, from S_{ij}, the measurement at location i for day j. For each location, the relative differences were averaged across all days of measurement to yield an intertemporal mean and time-associated standard deviation. The intertemporal means were ranked and graphically presented along with their time-associated standard deviations.

Soil moisture release curves were fitted for each depth of measurement at each of the 60 locations using the 14 d of soil water storage and soil matric potential measurements and the five parameter model of van Genuchten (van Genuchten and Nielsen, 1985) shown in Eq. [3].

$$\Theta_i = \Theta_r + \left\{\frac{\Theta_s - \Theta_r}{[1 + (\alpha\psi_i)^n]^{(1-\frac{1}{n})}}\right\} \quad [3]$$

The curves were fitted using Θ_s (saturated water content) values based on soil porosity, Θ_r (residual water content) values based on values published for Glendale clay loam (Hills et al., 1989), and Θ_i (instantaneous water content at ψ_i) and ψ_i (instantaneous ψ_m) values based on paired field observations for the 14 d of soil water storage measurement. The pore-size distribution index n was varied within theoretical limits and fixed at a value of 3.0 to provide the best agreement with experimental results; α (a curve parameter) was fitted by nonlinear regression using the NLIN procedure in SAS ver. 5.0 (SAS Institute, 1985).

The fitted curves were used to calculate the water release between boundary values of ψ_m representing each of the nine categories analyzed for each location. The calculated volumes released between limits of ψ_m were ranked and correlated with ranks of measured intertemporal mean ψ_m for each of the nine categories. The correlation coefficients between soil texture and field measured soil water storage were determined as were the correlation coefficients between soil texture and field measured ψ_m.

RESULTS AND DISCUSSION

A summary of soil texture, intercyclic mean water storage in the upper 0.6 m of soil 48 h postirrigation (presumed to be field capacity), intercyclic mean change in water storage during measurement cycles, and biomass production per square meter is presented by location in Table 1 along with field means, standard deviations, maximum and minimum values, and coefficients of variation for each of these parameters. The texture of the surface layer (0–20 cm) is relatively uniform compared with the variability of the second (20–40 cm) and particularly the third layer (40–60 cm) as evidenced from the lower coefficient of variation. This lower variability of a surface horizon in a cultivated field is not surprising

Table 1. Summary of percentage silt + clay by depth, intertemporal mean water storage in the upper 0.6 m 48 h postirrigation (Field Cap.), intercyclic mean water storage change (Δ), and biomass production.

	Silt + clay Soil depth (m)				Mean soil water storage		Biomass production
	0.0–0.2	0.2–0.4	0.4–0.6	0.0–0.6	Field cap.	Δ	
	%				m		kg m^{-2}
Mean	79.68	84.63	79.62	81.31	0.2535	0.0351	0.501
SD	2.37	6.43	17.70	7.03	0.0244	0.0076	0.202
Max.	87.4	99.4	99.4	92.10	0.293	0.057	1.22
Min.	74.8	58.6	29.1	61.50	0.190	0.021	0.21
CV, %	2.97	7.60	22.23	8.64	9.6109	21.5899	40.316

since tillage and field leveling tend to mix the upper soil layer more than soil below the depth of normal cultivation practices. The means of textures and coefficients of variation are very similar for the second soil layer (20–40 cm) and the combined soil layer (0–60 cm).

Locations 55, 65, and 75 were deleted from analysis because of an apparent lack of total soil wetting after irrigation. It is unclear whether this was caused by clogged emitters along the trickle tape or by excessive drainage in this part of the field that limited lateral movement away from the emitter. The second reason would be in agreement with the determinations of Or (1996).

Regression of intracyclic change in water storage against biomass production indicated no clear relationship between biomass and the change of soil water storage. Therefore we find no reason to assume that the changes in water storage due to evapotranspiration varied greatly among locations. The relationship between biomass production and the season-long mean ψ_m was also poorly correlated, indicating that ψ_m was maintained above critical threshold values at all locations throughout the growing season and that crop water availability did not limit biomass production.

Temporal Stability of Soil Water Storage Measurements

The matrix of Spearman's rank correlation coefficients from comparisons of soil water measurements made at 57 locations on all 14 d of record is presented in Table 2. All correlation coefficients in this matrix are significant at the 0.01 probability level and most are significant at the 0.001 probability level. This high level of temporal stability showed no time-associated drift, as evidenced by the constancy of the coefficients for the period of measurement.

Plots of ranked intertemporal means and time associated standard deviations of relative differences of measured soil water storage from the daily field mean presented in Fig. 2 also indicate a high level of temporal stability among locations. If the criterion for selecting a single location for measurement was defined by a reliable estimation of the mean to within 5%, several of the locations would suffice. Locations 34 and 41 are particularly good locations for measurement, as they lie near the field mean and have very low variances. Locations 13 and 21 are reasonably good estimators of the driest conditions in the field, which is not surprising since both locations have soils with relatively high percentages of sand in the upper 0.6 m. In a similar manner, Locations 62 and 82 are good estimators of the wettest conditions in the field and have soils with relatively low percentages of sand in the upper 0.6 m. The Spearman's rank correlation coefficient for the comparison of mean soil water storage rank with the percentage of soil particles <50-μm diam. was 0.681, which is significant at the 0.01 level of probability. The temporal stability of differences in soil water storage found in this field and its dependence on soil texture is consistent with the findings of other researchers (Ottoni, 1984; Vachaud et al., 1985; Kachanoski and deJong, 1988; van Wesenbeeck and Kachanoski, 1988; Jaynes and Hunsaker, 1989; Goovaerts and Chaing, 1993; Chen et al., 1995).

Temporal Stability of Soil Matric Potential Measurements

The cumulative probability plot of ψ_m on the day of most negative field mean matric potential and the first

Table 2. Matrix of Spearman's rank correlation coefficients from comparisons of soil water storage measurements made at the 57 field locations on all 14 d of record. All comparisons were significant at $P < 0.01$.

	5 Apr.	10 Apr.	17 Apr.	19 Apr.	27 Apr.	30 Apr.	9 May	13 May	17 May	22 May	24 May	30 May	2 June	6 June
5 Apr.	1.0													
10 Apr.	0.92	1.0												
17 Apr.	0.93	0.96	1.0											
19 Apr.	0.87	0.95	0.86	1.0										
27 Apr.	0.87	0.87	0.91	0.86	1.0									
30 Apr.	0.89	0.95	0.92	0.98	0.88	1.0								
9 May	0.91	0.89	0.95	0.87	0.92	0.91	1.0							
13 May	0.91	0.95	0.93	0.96	0.88	0.98	0.92	1.0						
17 May	0.91	0.91	0.94	0.90	0.91	0.94	0.97	0.96	1.0					
22 May	0.87	0.92	0.90	0.93	0.83	0.96	0.89	0.96	0.91	1.0				
24 May	0.89	0.91	0.93	0.92	0.89	0.95	0.94	0.95	0.96	0.97	1.0			
30 May	0.80	0.88	0.87	0.92	0.83	0.93	0.87	0.94	0.90	0.95	0.93	1.0		
2 June	0.81	0.84	0.88	0.86	0.85	0.89	0.89	0.90	0.91	0.93	0.96	0.94	1.0	
6 June	0.89	0.89	0.91	0.94	0.87	0.96	0.91	0.97	0.94	0.98	0.98	0.95	0.94	1.0

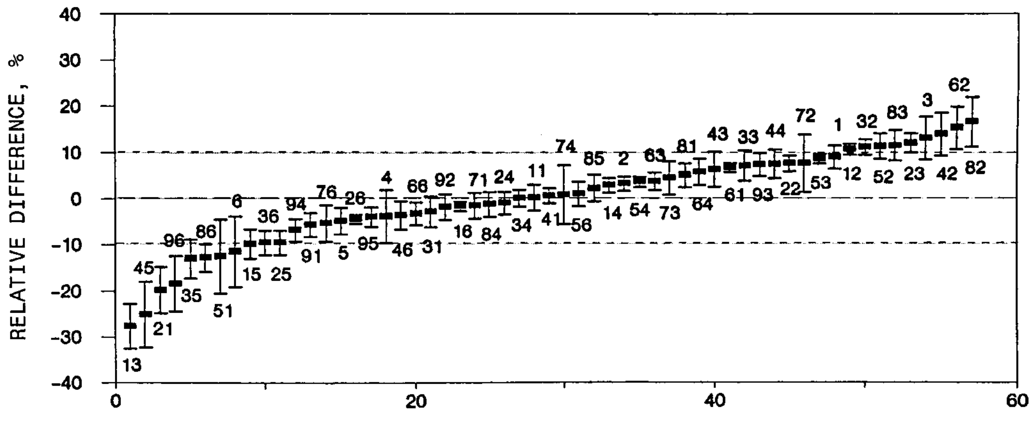

Fig. 2. Ranked intertemporal relative difference from the spatial mean water storage. Means are represented by blocks, and the associated intertemporal standard deviations are represented by vertical bars. Numbers refer to measurement locations.

day of measurement in that same irrigation cycle is presented in Fig. 3. From the linear cluster of points with low variance representing the measurements taken on 30 April, it appears that initially ψ_m was high and the soil profile was fully wetted at all locations. The linear pattern shown for 30 April in Fig. 3 was typical for the first date of measurement after each irrigation. The distribution of measurements taken on 9 May shows more variability with respect to the mean. The major portion of the curve for the 9 May measurements is also

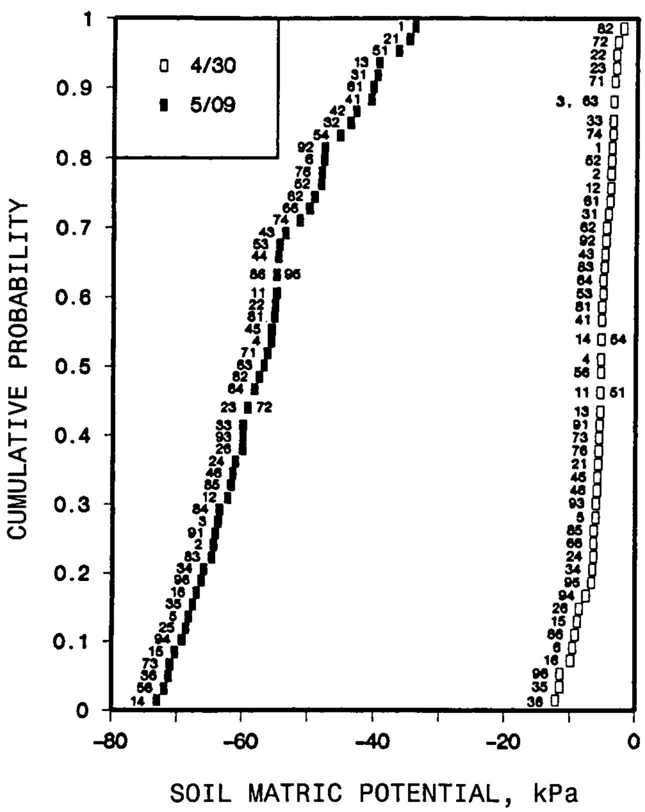

Fig. 3. Cumulative probability function of ψ_m for the day of the lowest spatial mean ψ_m (5/09) and the first day of measurement in the same irrigation cycle (4/30) for measurements representing the average across the three depths of measurement. Numbers refer to measurement locations.

relatively linear up to the 0.8 cumulative probability level. The nonlinear portion of the curve above the 0.8 cumulative probability level represents locations in which ψ_m did not change as much as the soil spatial mean, and these locations have a great influence on the arithmetic mean ψ_m. Logarithmic transforms of ψ_m measurements as suggested by Hendrickx and Wierenga (1990) did not noticeably improve the linearity of the cumulative probability distributions. The Kolmogorov D tests for normality ($P < 0.1$) performed on the observations on individual days indicated that the nature of the distribution tended to change with the mean. A summary of ψ_m statistics is presented by day of measurement in Table 3.

Five of the nine matrices of Spearman's rank correlation coefficients are presented in Table 4. Matrices are composed of comparisons of ranks observed from days on which the spatial mean ψ_m was within the range of limits given above each matrix. A high degree of correlation may be observed between the ranks of ψ_m on different days, many of which were in different irrigation cycles. The degree of correlation noted was not as great as that for soil water storage, but that is to be expected considering the physical problems encountered with ψ_m measurements. In most cases, however, the correlations between different days was significant ($P < 0.01$). The correlation appears to degrade with increasing time lags as evidenced by the smaller coefficients..

The plots of the ranked intertemporal means and time-associated standard deviations of relative difference are presented in Fig. 4 for four ranges of ψ_m commonly used for irrigation scheduling. The greater amount of variability among the observed relative differences compared with that for soil water storage is evident from the fact that the plots for ψ_m require a relative difference scale 2.5 times larger to contain all the observations. At moderately high mean ψ_m of -30 to -25 kPa, Locations 5, 26, and 93 appear to be good low variance estimators of the mean, only slightly overestimating it. These same three locations slightly underestimate the mean at lower ψ_m.

It seems apparent that although measurements within a given range of mean ψ_m may show temporal stability

Table 3. Field mean ψ_m for measurements representing the field spatial average across the three depths of measurement, number of locations, and related statistics for the 46 d of measurement.

Date	Locations	Soil matric potential (kPa)				CV	Normal? ($P < 0.1$)
		Mean	SD	Min.	Max.		
	n					%	
5 Apr.	44	−44.0	9.2	−59.7	−19.2	21.0	no
10 Apr.	37	−15.7	5.6	−32.0	−8.7	35.4	yes
12 Apr.	48	−19.4	7.7	−37.2	−9.9	39.9	yes
14 Apr.	50	−31.8	11.4	−55.9	−13.5	35.9	yes
17 Apr.	52	−49.2	12.9	−69.8	−16.8	26.2	yes
19 Apr.	38	−5.5	4.5	−21.9	−0.8	82.4	yes
21 Apr.	51	−6.3	3.8	−23.2	−2.1	59.7	yes
22 Apr.	54	−18.3	6.4	−33.9	−6.1	35.2	no
24 April	54	−23.7	8.8	−47.1	−11.1	37.0	no
25 Apr.	56	−32.4	12.2	−55.9	−9.9	37.8	no
26 Apr.	55	−39.8	10.2	−63.2	−20.0	25.6	no
27 Apr.	55	−47.5	10.1	−70.5	−28.2	21.1	no
30 Apr.	52	−5.7	2.3	−12.2	−2.1	39.6	yes
2 May	54	−8.2	3.3	−21.2	−3.4	40.7	yes
3 May	56	−14.6	5.2	−31.0	−5.6	35.6	yes
4 May	57	−23.2	7.6	−43.6	−9.7	32.7	no
5 May	57	−35.0	9.2	−56.3	−17.9	26.3	no
6 May	57	−41.4	10.0	−63.5	−23.7	24.2	no
7 May	57	−46.9	10.3	−67.8	−28.8	22.0	yes
8 May	57	−51.8	10.1	−70.0	−32.6	19.5	no
9 May	57	−56.4	10.2	−73.0	−34.1	18.0	no
13 May	57	−6.3	2.1	−11.9	−2.3	33.2	yes
14 May	57	−10.5	3.2	−20.2	−5.1	30.0	no
15 May	57	−16.3	4.8	−30.9	−8.8	29.2	no
16 May	57	−20.0	6.1	−36.0	−8.2	30.5	no
17 May	57	−25.5	7.3	−43.2	−12.2	28.5	no
19 May	57	−38.4	9.3	−61.1	−19.1	24.2	no
22 May	51	−5.3	2.3	−13.9	−2.2	42.6	yes
23 May	57	−7.3	3.3	−17.8	−2.0	45.0	yes
24 May	57	−16.0	5.3	−30.1	−8.6	32.9	yes
25 May	57	−25.6	8.6	−46.8	−9.3	33.4	no
26 May	57	−35.4	10.6	−60.8	−14.0	29.9	no
30 May	51	−4.9	2.3	−15.0	−1.6	47.4	yes
31 May	55	−8.7	3.5	−20.5	−3.5	39.6	yes
1 June	54	−12.9	4.9	−29.6	−4.9	38.2	yes
2 June	55	−21.0	7.4	−42.1	−9.2	35.4	yes
3 June	55	−27.4	9.3	−53.9	−11.5	33.8	no
6 June	55	−7.3	2.5	−15.1	−3.1	34.8	no
7 June	56	−9.8	4.1	−23.5	−4.1	41.4	yes
8 June	56	−14.9	6.5	−38.0	−5.5	43.6	yes
9 June	56	−22.7	9.7	−57.2	−8.1	42.9	no
11 June	56	−7.2	6.7	−40.9	−1.8	92.1	yes
12 June	57	−11.4	7.5	−42.1	−3.4	66.3	yes
13 June	56	−17.6	9.2	−42.7	−4.1	52.4	yes
14 June	56	−23.2	9.5	−46.0	−7.5	40.9	yes
15 June	56	−29.2	10.1	−50.3	−9.8	34.6	no

among the locations, the ranks of the measurements tend to drift, often directionally, between ranges of ψ_m. Even locations at the extremes of ranking such as Locations 61 and 94 lose their position, again often directionally, between ranges of mean ψ_m. The nonlinear nature of the soil water characteristic curve and differences of the curves for the soils at each location are two probable causes of this phenomenon. This is illustrated by the differences in two in situ soil water release curves presented in Fig. 5 that were developed from field measurements during the course of this study. While this drift associated with the magnitude of the ψ_m initially appears problematic, it actually is a minor impediment to the practical application of this technique. Careful examination of the highly significant Spearman's rank correlation coefficients presented in Table 5 leads us to conclude that although the absolute order of ranks changes between ranges of mean ψ_m, an ideal location chosen for one range will estimate the mean in another range without great error. Fig. 6 shows how constantly Points 5, 26, and 93 estimate the field mean and Points 35 and 62 estimate the extremes. For almost all days of measurement, these field locations offer measurements that track their respective percentages of field soil matric potential.

The field where this study was conducted was used to test the response of three varieties of cotton to five different levels of drip irrigation during the 1986, 1987, and 1988 growing seasons. Tensiometer data collected in the 12 control plot locations during 1986, 1987, and 1988 were analyzed to determine whether temporal stability patterns noted in 1989 were present in previous years. Temporal stability of ψ_m was present in these previous growing seasons, although to a lesser extent than in 1989. Measurements from these years indicated that temporal stability was not reliable beyond just a few days into the irrigation cycle, a condition very similar to that noted by Hendrickx and Wierenga (1990). The lower temporal stability may be due to more frequent shallow irrigations (0.025 m per application vs. 0.1 m per application in 1989) resulting in less than complete wetting of the entire profile.

Table 4. Matrices of Spearman's rank correlation coefficients from comparisons of ψ_m made at the 57 field locations on days for which the spatial mean ψ_m fell within the range specified above each matrix. Values of ψ_m were averages across the three depths of measurement. All comparisons were significant $P < 0.01$ unless noted by daggers.

	−10 kPa < ψ_m −5 kPa										
	19 Apr.	21 Apr.	30 Apr.	2 May	13 May	22 May	23 May	31 May	6 June	7 June	11 June
19 Apr.	1.0										
21 Apr.	0.74	1.0									
30 Apr.	0.67	0.82	1.0								
2 May	0.51	0.85	0.81	1.0							
13 May	0.45	0.77	0.77	0.82	1.0						
22 May	0.63	0.69	0.76	0.79	0.80	1.0					
23 May	0.42	0.70	0.72	0.86	0.70	0.84	1.0				
31 May	0.32†	0.55	0.57	0.73	0.67	0.75	0.84	1.0			
6 June	0.25‡	0.41	0.51	0.51	0.64	0.67	0.49	0.61	1.0		
7 June	0.26‡	0.35†	0.49	0.61	0.54	0.74	0.75	0.88	0.68	1.0	
11 June	0.33†	0.40	0.53	0.50	0.48	0.59	0.63	0.64	0.45	0.63	1.0

	−20 kPa < ψ_m ≤ −15 kPa					
10 Apr.	12 Apr.	22 Apr.	15 May	24 May	13 June	
10 Apr.	1.0					
12 Apr.	0.91	1.0				
22 Apr.	0.73	0.79	1.0			
15 May	0.53†	0.46	0.65	1.0		
24 May	0.15‡	0.26‡	0.53	0.79	1.0	
13 June	0.24‡	0.28‡	0.44	0.59	0.68	1.0

	−30 kPa < ψ_m ≤ −25 kPa			
17 May	25 May	4 June	15 June	
17 May	1.0			
25 May	0.85	1.0		
4 June	0.83	0.92	1.0	
15 June	0.64	0.75	0.77	1.0

	−40 kPa < ψ_m ≤ −35 kPa		
	26 Apr.	19 May	26 May
26 Apr.	1.0		
19 May	0.77	1.0	
26 May	0.72	0.85	1.0

	−50 kPa < ψ_m ≤ −45 kPa		
	17 Apr.	27 Apr.	7 May
17 Apr.	1.0		
27 Apr.	0.79	1.0	
7 May	0.61	0.84	1.0

† $0.01 < P < 0.1$
‡ $0.1 < P$

Comparisons made between years did not indicate temporal stability of measured ψ_m extended between years. It appears that removal and reinstallation of the tensiometers each season resulted in placement that was not precise enough to measure the very same soil individual measured in previous years. Another plausible reason for the lack of continuity between years was the effect of tillage and soil preparation performed on the field between growing seasons. Logsdon and Jaynes (1996) noted changes in the hydraulic conductivity in a field soil that were caused by tillage and resulting reconsolidation of the soil. Further, soil structure has been shown to have a greater influence than texture on in situ soil water characteristic curves developed from field measured data (Greminger et al., 1985), and soil structure is expected to change with mechanical disturbance.

The search for a simple covariant with ψ_m rankings yielded disappointing results. While significant correlations between rankings of percentage silt plus clay and rankings of ψ_m could be found at high ψ_m, significance dropped drastically at ψ_m below −25 kPa and even showed some negative correlation at ψ_m of −45 kPa and below. The significance observed at high ψ_m may be an artifact of slower drainage caused by the lower percentage of sand. The reduced significance and negative correlations noted at lower ψ_m may indicate that although soils with more silt and clay may hold more water between irrigations, they may release less of that water between limits of ψ_m. It appears that the complexity of the relationship between soil texture and ψ_m precludes the use of soil texture analysis to predict ideal measurement locations.

Correlation between rankings of soil water characteristic based predictions of water released between limits of ψ_m and the rankings of measured ψ_m yielded results opposite to those for soil texture. At low ψ_m, correlation could be shown, but at higher ψ_m, insignificant and negative correlation was observed. Examination of the data from which the curves were developed showed a great deal of scatter of measured soil water contents at high ψ_m, most probably resulting from the hysteretic effects frequently observed with soil wetting.

CONCLUSIONS

The results obtained from this study strongly indicated that the concept of temporal stability of spatially measured soil water parameters is valid. Excellent temporal stability of soil water storage was observed to be consistent with those of others investigating this phenomenon (Ottoni, 1984; Vachaud et al., 1985, Kachanoski and de Jong, 1988; van Wesenbeeck and Kachanoski, 1988; Jaynes and Hunsaker, 1989; Goovaerts and Chiang, 1993; Chen et al., 1995). It seems apparent from the highly significant correlation between soil texture and soil water storage, that soil texture may be a convenient criterion for locating soil water content measurement locations for field mean or extremes estimation.

In contrast to previous studies, we were able to show temporal stability of spatially measured ψ_m in a field soil. Temporal stability of ψ_m was evident in 1989 and, to a lesser extent, in previous years. The stability observed seemed to be affected by some time-dependent process, however, and it is unclear whether this was caused by some factor related to cultivation history. Conservation

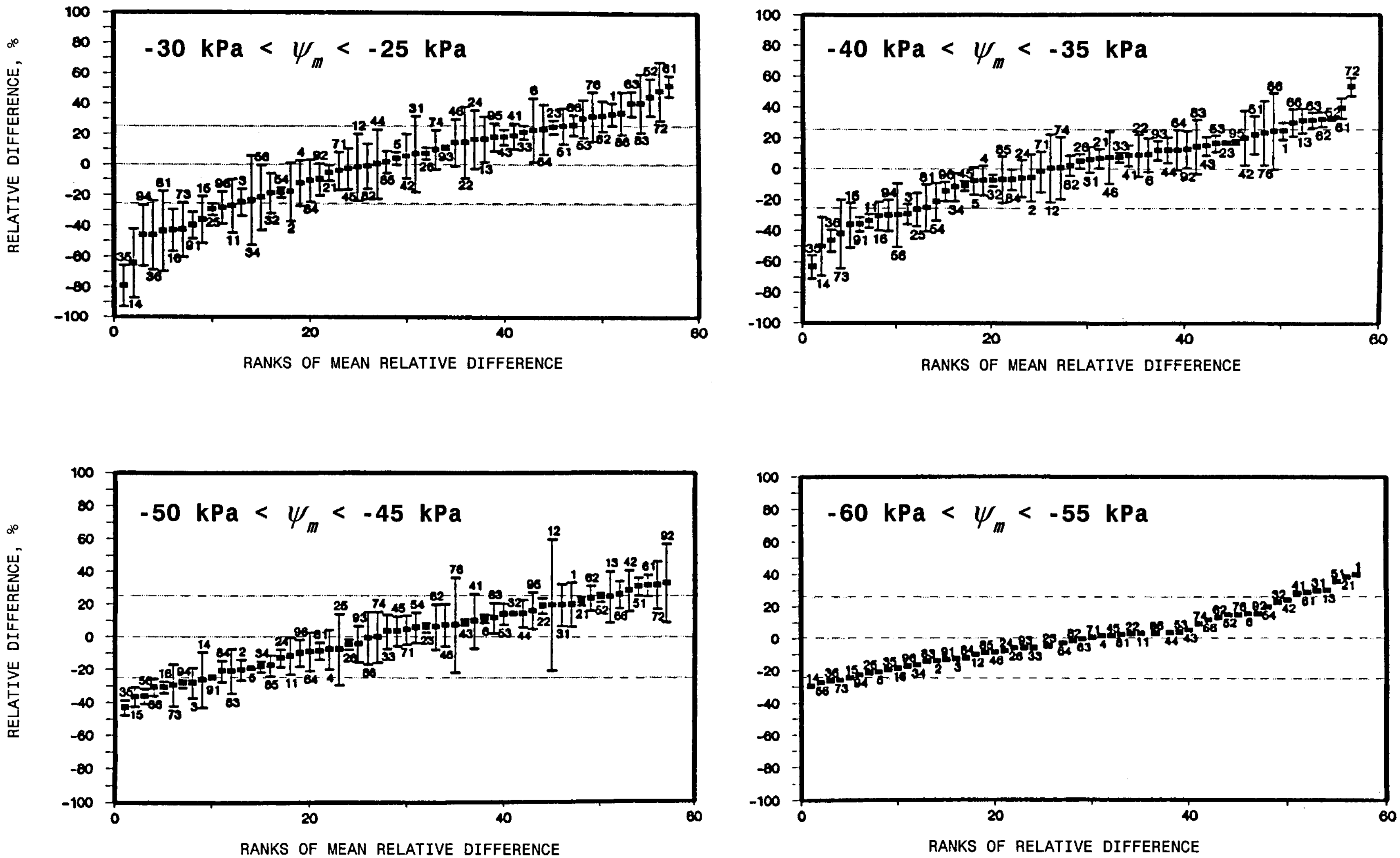

Fig. 4. Ranked intertemporal relative difference from the spatial mean ψ_m for measurements representing the average across the three depths of measurement. Means are represented by blocks, and the associated intertemporal standard deviations are represented by vertical bars. Numbers refer to measurement locations.

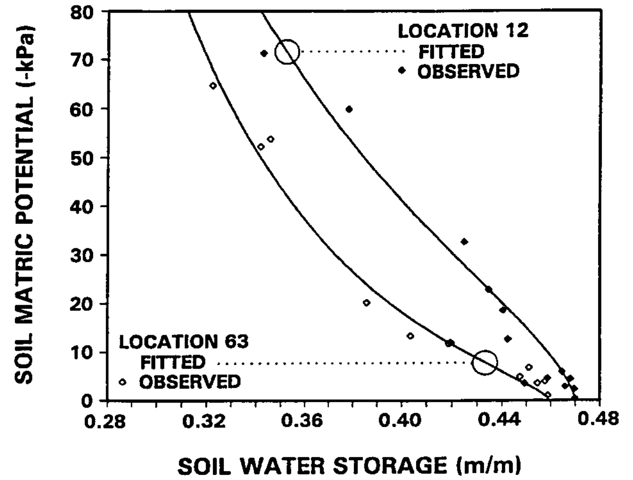

Fig. 5. Comparison of soil water release characteristic curves from the 0.3-m depth at Locations 12 and 63 showing the different shapes and intercepts of the curves and the different volumes of water release between the limits shown. Of particular interest are the different ranges of ψ_m over which each curve exhibits maximum water release.

tillage is being implemented on increasing acreage. It is logical to expect greater stability of soil physical properties such as soil structure and bulk density in soils managed under conservation tillage. This greater temporal stability of soil physical factors, coupled with the advent of permanent and semipermanent ψ_m sensors (Phene et al., 1989; Fredlund et al., 1992; Baumgartner et al., 1994), may reduce the time-dependent drift we observed and the problems we encountered with year-to-year sensor placement. Permanent sensors, placed in as few as one or two appropriate locations would allow automation of irrigation based on critical values of ψ_m. The slight drift of ranks between ranges of field mean ψ_m suggests that the technique of mean estimation from one location is best applied to situations where a narrow range of critical ψ_m would be of interest or where a limited error in mean estimation could be tolerated.

The importance of full wetting of the soil profile limits the usefulness of this technique to flood or furrow irrigated fields. From analysis of the prior 3 yr of tensiometer data and from results of previous studies of soil matric potential variability (Saddiq et al., 1985; Hendrickx and Wierenga, 1990) it seems obvious that reliable temporal stability is absent when this condition is not satisfied. It should be noted that a possible additional factor in previous years and studies may have been the uneven runoff and infiltration of precipitation, as suggested by Kachanoski and de Jong (1988). The period of data collection in 1989 was without measurable precipitation, thereby removing topography as a factor.

Table 5. Matrix of Spearman's rank correlation coefficients for comparisons of the ranked mean relative difference of the 57 field locations for each of the nine ranges of field mean Ψ_m analyzed. All comparisons were significant at $P < 0.01$ unless noted by daggers.

	Ψ_m								
ψ_m	5–15	15–	25–	30–	35–	40–	45–	50–	55–
5–15	1.0								
15–25	0.87	1.0							
25–30	0.74	0.89	1.0						
30–35	0.51	0.78	0.67	1.0					
35–40	0.69	0.86	0.93	0.74	1.0				
40–45	0.31†	0.49	0.50	0.44	0.61	1.0			
45–50	0.52	0.71	0.66	0.65	0.82	0.75	1.0		
50–55	0.43	0.59	0.65	0.45	0.76	0.79	0.88	1.0	
55–60	0.37	0.52	0.57	0.40	0.68	0.77	0.84	0.98	1.0

† $0.01 < P < 0.1$.

Further investigations into temporal stability of spatially measured soil matric potential are needed before it may be accepted and routinely used. In particular, the problems noted with time-dependent drift within a range of field mean soil matric potentials and drift between ranges of mean potential need to be addressed. Another area needing further research is the identification of a simple and reliable covariant for soil matric potential. Poor correlation of ranked soil matric potentials and soil texture preclude identification of ideal locations from textural analysis, and the time and instrumentation necessary to develop in situ soil water charac-

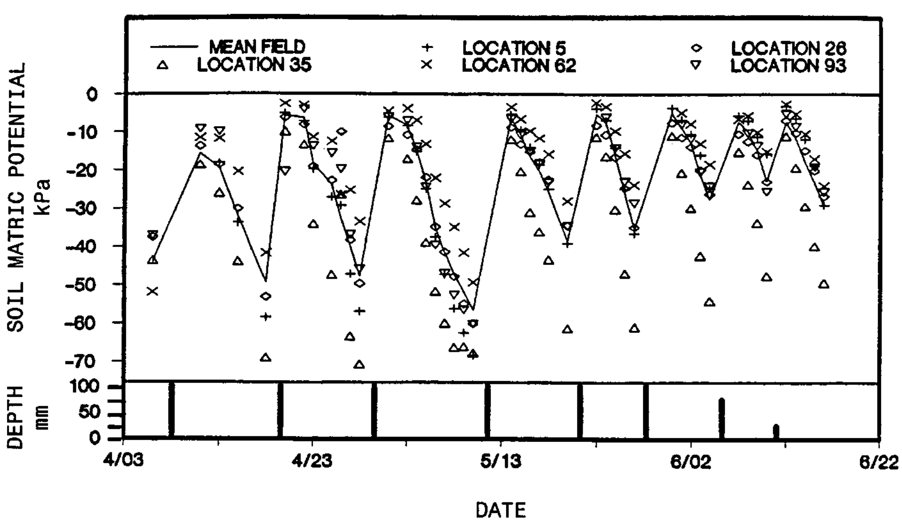

Fig. 6. Time behavior of measured ψ_m at selected field locations representing three mean estimators (5, 26, and 93) and two estimators of the extrema (35 and 62) for measurements representing the average across the three depths of measurement.

teristic curves at several locations in a given field limit the usefulness of this technique to find ideal measurement locations. This study proved that temporal stability of soil water storage and ψ_m could be shown in a heterogenous soil of a small field. The range of soil water storage and soil texture variability noted in this small field is consistent with that shown for many landscape scales, including watersheds (Zhang and Berndtsson, 1988). If the phenomenon of temporal stability of measured soil matric potential patterns can be validated for other soils, this may prove to be a powerful soil water management technique.

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